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A Major Survey of the National Ignition Facility

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A MAJOR SURVEY OF THE NATIONAL IGNITION FACILITY*

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Abstract

The National Ignition Facility (NIF) is an inertial confinement fusion project being built at Lawrence Livermore National Laboratory (LLNL) for the Department of Energy (DOE). The project is comprised of two buildings and the high technology equipment. The NIF houses 192 separate laser beams that generate approximately two megajoules of energy and 500 terawatts of power. The laser beams travel through a large optical system that contains over 7,500 large-aperture optical components (40 cm by 40 cm) and approximately 30,000 small-aperture optical components (less than 20 cm diameter). The NIF laser will be enclosed in a building that is approximately 200 meters in length (l) by 100 meters in width (w) by 15 meters in height (h) scheduled for completion by the end of 2002. A 0.5 mm target will be positioned inside a 10 meter sphere in the Target Building which measures approximately 35 meters (l) by 90 meters (w) by 30 meters (h). To achieve optimum laser operation the optics will require precision positioning and alignment. As a result, the mechanical components that support the optics require accurate positioning. State-of-the-art surveying, measuring techniques, and uncertainty and error analyses are being used to measure the control network and mechanical components. These include laser trackers, total stations, precision digital levels, and simulations of measurement scenarios.

In February of this year the Lawrence Livermore National Laboratory NIF Precision Survey Group (PSG) completed a planned survey of the facility to establish an intermediate control network. This control network is to be used to begin installing the mechanical components, which include over 40 large vessels (3 x 3 x 10 meters), over the next year. The requirement is to have a control network accurate to +/- 3 mm, 3 sigma. The majority of the control network was measured using total stations and precision leveling. A laser tracker, in combination with total station and precision level measurements, was used to help strengthen the network vertically for the 30-meter tall target building. The results of surveying 1032 monuments produced a much more accurate control network than required. This paper discusses the planning and execution of the survey and the results of the data reduction and analysis, including instrument performance and building settlements. The survey results also indicate that the future precision control network (+/- 0.3 mm, 3 sigma) is attainable provided the structural settlements dampen to an acceptable level.

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Introduction

This report discusses the planning and strategy for accomplishing the goals of the NIF Intermediate Control Network (ICN) and the results of the measurements from processing of the data in developing the ICN.

The ICN comprises in excess of 1000 monuments which will be used for setting Contractor Subcontract Package (CSP) 13 components in the Laser Target Assembly Building (LTAB). Some of these components are as large as 3 X 3 X10 meters. The facility is divided into several rooms which include Laser Bay 1 and Laser Bay 2, each measuring approximately 150 (L) X 25 (W) meters; Switchyard 1 and Switchyard 2, each measuring approximately 35 (L) X 25 (W) X 30 (H) meters; and the target bay, a cylinder measuring approximately 30 meters in diameter and 30 meters in height. The switchyards and target bay make up the Target Building. Figure 1 illustrates the facility and the identified rooms.

Figure 1 LTAB layout (under construction).

The NIF houses 192 separate laser beams that generate approximately two megajoules of energy and 500 terawatts of power. The laser beams travel through a large optical system (Figure 2) that contains over 7,500 large-aperture optical components (40 cm by 40 cm) and approximately 30,000 small-aperture optical components (less than 20 cm diameter). A 0.5 mm target will be positioned inside a 10 meter sphere located in the Target Building.

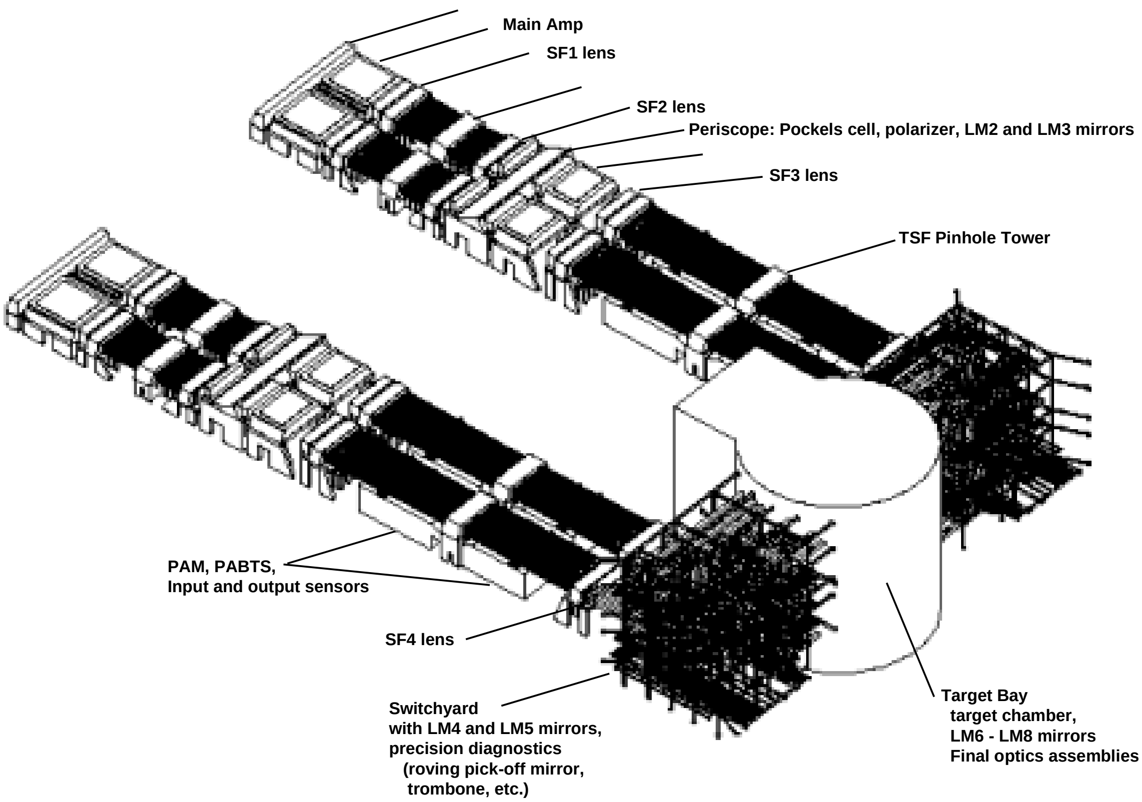

Figure 2 Schematic of optical system in the Laser and target Area Building (LTAB).

The laser beams are generated, amplified and filtered in the two laser bays. The beams then travel into the switchyards where they are split into upper and lower quads (groups of four beams) and then turned and directed towards the target bay. Once in the target bay the quads hit a group of 3 mirrors that direct the beams toward the target. Just before the beams enter the target chamber they undergo a frequency conversion from infrared to ultraviolet and then are focused down to a 1 mm spot.

The CSP 13 schedule calls for rough placement of vessels and structures in the laser bays from June00 to Dec00. The control network (Intermediate Control Network) required to support rough placement must be accurate to $\leq \pm 3$ mm, (3σ, i.e., 99.7% confidence in the location of any given monument). A Precision Control Network (PCN), accurate to $\leq \pm 0.3$ mm (3σ) is required for final installation alignment by the end of CSP 13. A Skeleton Network with an accuracy of $\leq \pm 5$ mm, 3σ was established in June 1999.

The purpose of the ICN is to provide CSP13 contractors control network monuments (CNMs) with coordinates from which they can install and correctly position components and vessels relative to the NIF Global Coordinate System (NGCS). The network is represented by 1032 CNMs spread over the laser bays, switchyards, and target bay (all seven levels). For the laser bays, all the CNMs are located in the floor. For the target building the majority of the CNMs are located in the walls and structures. A few are installed in the floor at each level for controlling the gravity plane and for monitoring deformation using a precision level. Figure 3 illustrates a plan view of the CNM pattern for Level 3 (0.0ft elevation)

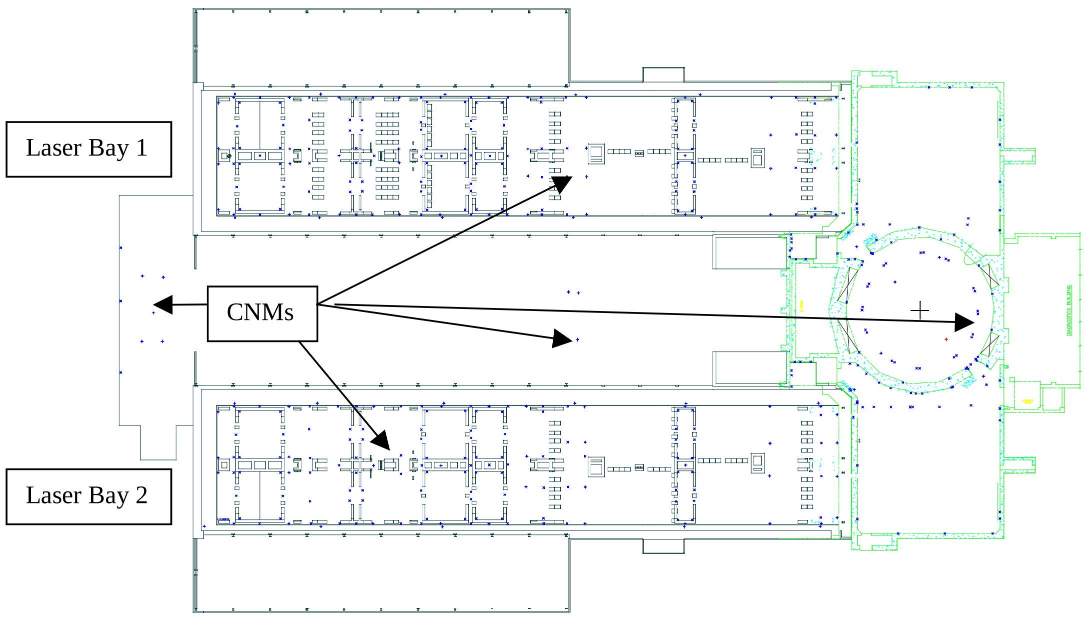

Figure 3 Layout of CNMs on the 0.0ft elevation (Level 3)

Comparison of the ICN to the previous network (Skeleton Network) provides information regarding building displacement and deformation. Confidence in the accuracy of the ICN will diminish with time at a rate determined by continued settling and deformation.

Planning the Survey

Planning the survey involved determining where total station observations, using a Wild TC2002, would be adequate and where using a SMX 4500 laser tracker for observations was critical. Because of the superior performance of the TC2002 we determined the only critical need for a laser tracker was for observations in the target building to strengthen ties between the floors. The TC2002 would be the workhorse for the survey. Leveling would be performed using a Leica NA3003 precision digital level throughout the laser bays and on each floor of the target building.


Figure 4 Laser bay 2 with concrete support structures

Personnel from the Stanford Linear Accelerator Center (SLAC) Metrology Group assisted in the layout and simulation of the survey plan for the laser bays. A layout was generated for each total station location and the observations to CNMs by inputting CNM design values into the building drawing using Autocad Land Development. The large concrete support structures were already in place and lines of sight were limited as can be seen in Figure 4. An instrument location was drawn (Figure 5) along with rays from the instrument to the CNMs to be measured. A hardcopy was printed along with a worksheet listing the CNMs to be measured, pertinent information for the instrument location, and an area for field notes (file record). The worksheets proved to be valuable in troubleshooting data files. Once all the station locations and respective observations were complete a simulation was run to calculate expected uncertainties for the observed CNMs. The simulation aided in determining if additional observations were needed. Crews were instructed to ensure each CNM was measured a minimum of three times, with reasonable geometry, from different instrument locations. A logging mechanism was incorporated to track the number of observations to the CNMs.

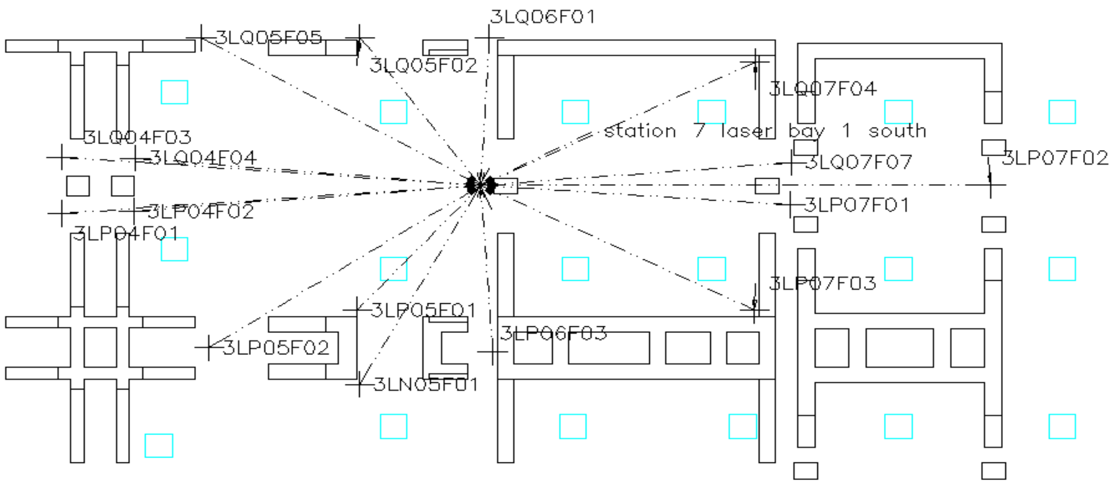

Figure 5 Typical total station observation layout.

The target building required a different, less structured, approach due to the numerous interferences. In the target building a laser tracker was to be positioned over each of four plummet lines. The plummet lines allowed vertical observations from level 1 up to level 7, approximately 27 meters in distance. A typical set up of a laser tracker on a plummet line is illustrated in Figure 6.

“Tophats”, which hold a spherically mounted retro-reflector (SMR), were to be mounted to the floor over the plummet holes. These were the “tie points” that would be used to connect the floors. The laser tracker would be located over a plummet line on one of the levels in the target bay (e.g., level 3). Observations would be made on the CNMs in the field of view of the laser tracker (on the walls and floor of level 3), the tophat targets in the plummet line, and the CNM located in the floor at Level 1. The CNMs in the floor at Level 1 are the only permanent CNMs in the plummet lines. The tophat CNMs are considered temporary and are only used to tie the levels together. The laser tracker would then be moved to the another plummet location on the floor. All four plummet lines on a level were to be completed before moving to the next level. The tie points and CNMs would also be measured with total stations set up on each level of the target building traversing around the cylinder and out onto mezzanines where observations to switchyard and laser bay CNMs would be made.

Figure 6 Typical laser tracker set up on a plummet line in target building

Software for data collection was improved to assist in reducing field errors. A new routine was developed to check the location of the CNM after it was measured, requiring two well known CNMs with appropriate geometry be observed first to resection the instrument. CNMs measured after resection were compared with a database for 3d distance from the station location using a pre-selected threshold. If the measured distance is greater than the threshold the operator is warned and can recheck the CNM name and the measured CNM. This check would only work for CNMs incorporated into the database either by previous measurement or by design. Some CNMs were new and not in the database. CNMs not in the database were documented by field notes. For leveling and laser tracker observations, the operators recorded CNM names as they were measured in addition to inputting names into the electronic field book. This provided a check for mistyped names.

The NIF Precision Survey Group did not have the capability to conduct such a large survey effort. ATT Metrology Services, Inc. (ATT) was contracted to provide instruments and operators and Johnson Controls was contracted to provide support personnel for the ATT operators.

ATT required instrument operators to participate in a hands-on instructional training session at their main office in advance to become familiar with field software, instruments, and measuring methodologies used at LLNL. This eliminated the need to train personnel at the beginning of the survey, thus significantly increased crew productivity.

In addition, procedures were written for instrument setup and note taking, naming convention for un-named CNMs and temporary points, and data downloading.

Executing the Survey

The survey began on February 14, 2000 and ended on March 7, 2000. The first day was dedicated to orientation and safety training. Two twelve hours shifts, with 7 crews working the day shift and 6 crews working the night shift, utilized 28 personnel. Of the 13 crews, eleven were used for total station observations. The remaining two crews were used for leveling and the laser tracker. The shifts were reduced to ten hours after the first week because sufficient progress had been made and to maintain a low error rate. Each shift had a lead person that would organize the shift work and provide problem solving for the crews. In addition, personnel from SLAC were present and available to assist in resolving technical issues.

Each crew was provided observation plans for a specific area and an electronic memory card (PCMCIA) that inserted into the data collector. At the end of the shift the crews would turn in their PCMCIA cards, observation plans, and field notes to the shift supervisor. A half-hour overlap of shifts provided communication opportunity for all crews to discuss problems and strategies and provide interaction to assist the next shift.

The shift supervisor evaluated the data (primarily looking for typos in names) on the PCMCIA card and uploaded files to the PSG server. A backup copy was also made on a Jazz cartridge. The card was then erased and stored for the next day.

Each total station crew received a set of observation plans at the beginning of the shift. The plans indicated an approximate position for instrument location and identified the CNMs to be observed. Instruments and targeting were calibrated and checked each shift because multiple crews used the same instrument and targeting. Each observation set was saved as a unique file. Initially, the operator would site on a standard Hubbs theodolite target to position the crosshairs of the instrument. The target was then replaced with a SMR for measuring range. After the range was measured the SMR was removed and the Hubbs target placed back in the CNM nest. The operator resighted the target and recorded horizontal and vertical angles. Two sets of frontsight and backsights were performed for each CNM observation. The data collection software performed statistical analysis on the observations and warned the operator if residuals exceeded pre-selected criteria. Operators repeated observation files that failed the statistical checks.

One crew was used solely for the laser tracker work on the plummet lines in the target building. The laser tracker was installed on its side on an instrument stand and positioned over one of the plummet lines as shown in Figure 6. Checks were made to ensure the optical path would reach the tophats on all levels. Calibration of the laser tracker in the sideways (lateral) orientation was determined to be unsuccessful after discrepancies of calculated coordinates for the same CNMs, measured from different laser tracker orientations, differed by millimeters. Several days were spent evaluating the discrepancies. The manufacturer was contacted and the calibration scenario described. The manufacturer determined the calibration routine was incorrect. They expedited a correct calibration routine, for the laser tracker in a lateral orientation, to LLNL and ATT personnel. The routine was implemented and several points checked along a plummet line.

There were a sufficient number of tophats such that the four plummet lines could be tooled. The laser tracker was positioned over a plummet hole with a tophat and the tophat SMRs measured above and below on the plummet line, as well as the CNMs in the field of view on the level. Because of the limited view with the laser tracker on its side, limiting observations to CNMs in the area, the laser tracker was rotated and identified as another instrument station. This produced a minimum of two observation files per location. The laser tracker was then moved to another plummet location. All the levels (seven) on the four plummet lines were measured. A total of 56 observation files were recorded in the laser tracker software program. These files were saved onto floppy disk and then copied onto the PSG server.

Observations using total stations were also made for all CNMs throughout the target building. In most cases, at least three observations were made on each CNM.. Redundancy and common CNMs between laser tracker and total station observations provided a rigorous traverse for the building. The weakest geometry for the survey network was the ties between the laser bays and the target building, primarily between laser bay 2 and switchyard 2.

Differential leveling was completed by a crew using a Leica NA3003 digital precision level and a 2-meter bar-coded rod. Differential heights were measured for a subset of the CNMs installed in the floors. Loops were measured, and closure checked, in order to help identify blunders. A total of 18 level files, with a total of 353 height differences, were recorded and uploaded for reduction.

There were numerous obstacles to deal with because of ongoing construction activities. When an area was not accessible because of construction the crew would be given a different observation plan for another accessible area. The pre-planning effort minimized the down time of crews.

Overall, the execution of the survey went very well. The pre-planning effort, by LLNL and SLAC, and the pre-survey training that ATT provided to the operators greatly improved efficiency and results.

Data Reduction and Adjustment Results

A total of 439 instrument files were collected, of which 435 were reduced and used in the adjustment and evaluating instrument performance. Five files were unusable. These files were identified as faulty during the measurement process by built-in checks the software provides (e.g., gun out of level). There was a 13% repair rate of the usable files. Most repairs were due to mistyped CNM names. These repairs consisted of going into the raw data file and correcting the error and re-reducing the file. There were 5,089 distances, 5,089 horizontal angles, 5,089 vertical angles, and 353 differential height measurements. The measured performance of each instrument listed below in Table 1 meets our expectations.

Instrument Measurement	Performance
Laser tracker range	0.039 mm
Laser tracker horizontal angle	3.6 seconds (18 urad)
Laser tracker vertical angle	2.4 seconds (12 urad)
Total station range	0.117 mm
Total station horizontal angle	0.94 seconds (5 urad)
Total station vertical angle	1.25 seconds (6 urad)
Digital level	0.034 mm

Table 1: The measured performance of survey instruments.

Figure 7 provides a graphical representation of the range residuals as a function of range measured for the SMX 4500 laser tracker. Figure 8 provides a similar graphical representation for eleven total station operators using six different Wild TC2002 total stations. The outliers for the distance residuals are most likely from environmental effects. There was a ten degree temperature difference between the level 1and level 7 of the target building which was not compensated in the laser tracker observations. In addition the floors and tophats at each level combined to make a tube through which the laser tracker beam passed through. No effort was made to minimize laminar conditions for the measurements.

The two laser bays were connected by observations to the CNMs installed in the corridors, connecting the middle of the two laser bays and at the east end of the LTAB, as illustrated in Figure 9. The connections between laser bays and switchyards were established by locating the total station in the large beam tube openings in the laser bay/switchyard walls, the personnel door openings, and other available open pathways and recording observations to the rooms. Many of these other pathways will not be available in future network surveys. Figure 10 is an elevation view of the target building illustrating the observations used to tie the different levels together. The four plummet lines used for measurements by the laser tracker are clearly visible.

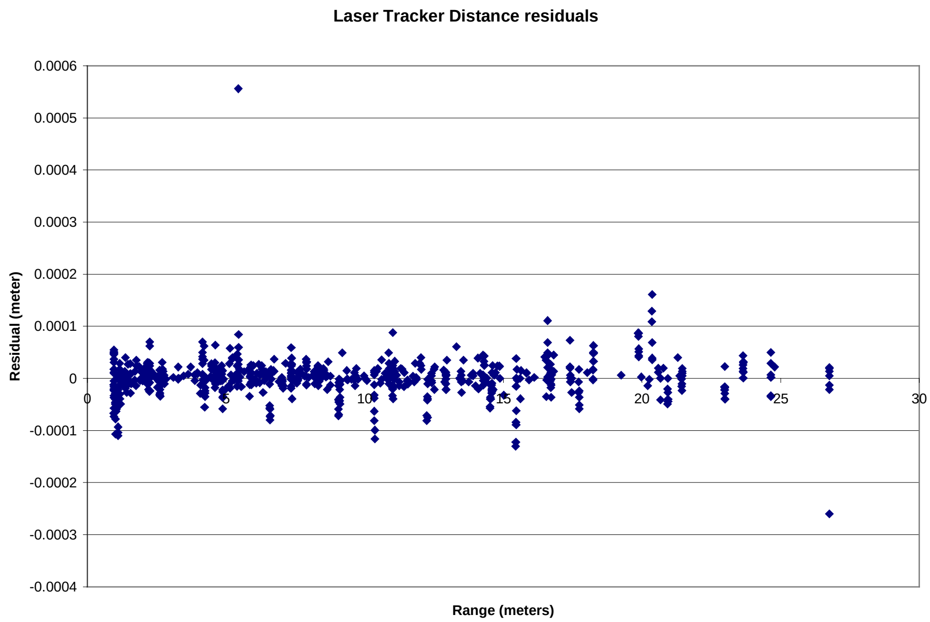

Figure 7 Plot of laser tracker distance residuals as a function of range.

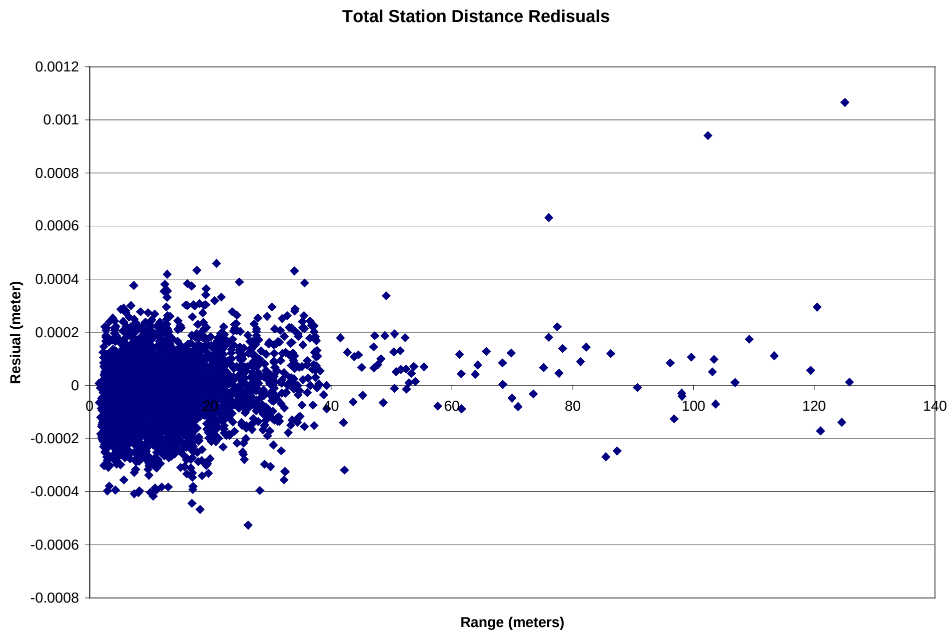

Figure 8 Plot of total station distance residuals as a function of range.

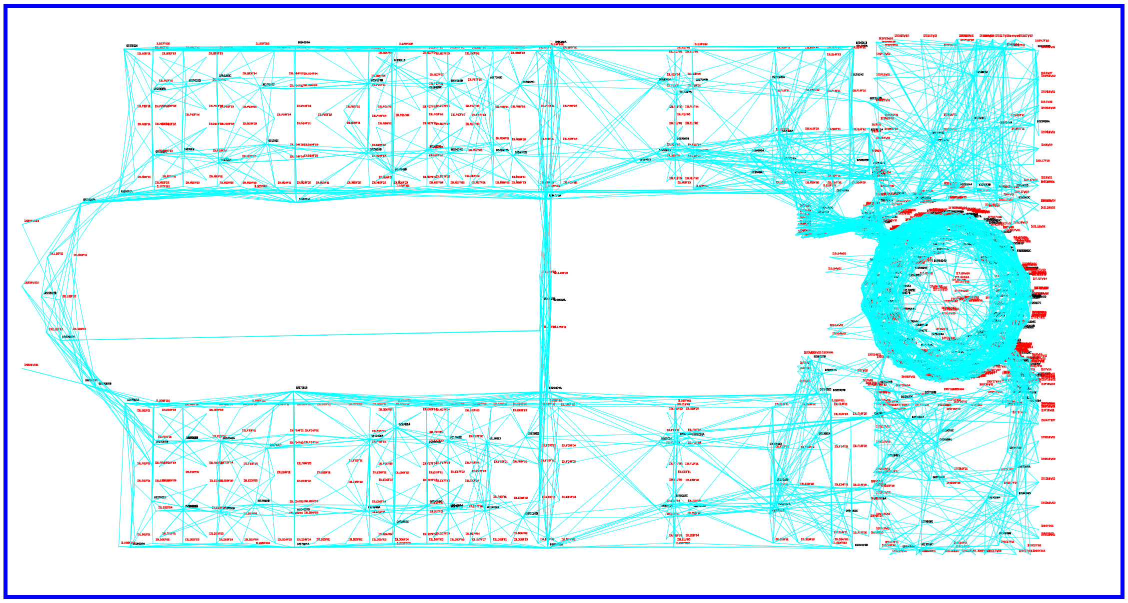

Figure 9 Plan view of survey observations in the LTAB.

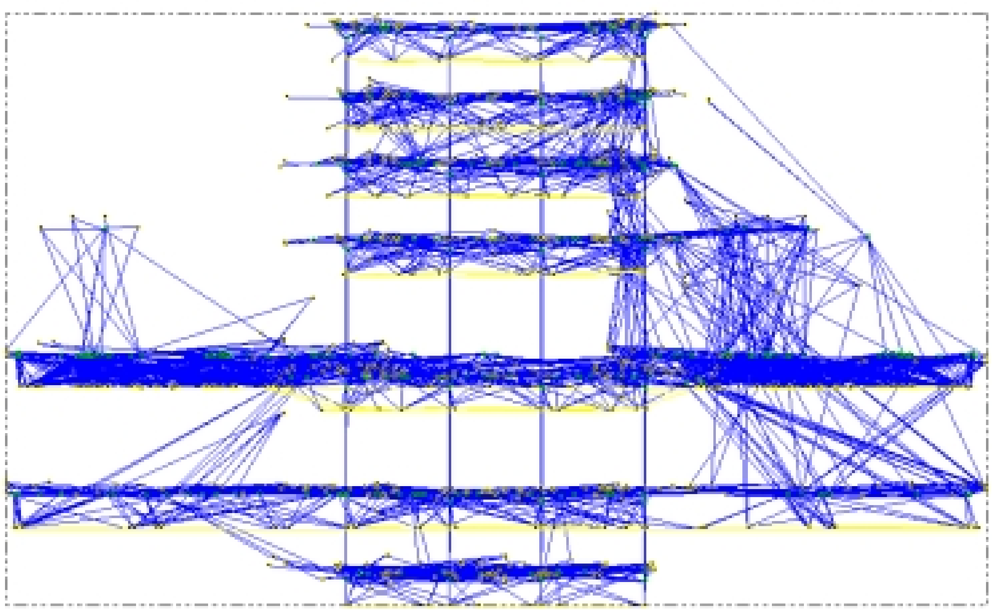

Figure 10 Elevation view of target building observations illustrating the four plummet lines.

As survey data was collected and uploaded in the office it was processed and small adjustments were run for localized portions of the building. For example, as each level in the target building was surveyed the data for the specific area was assembled and an adjustment was run to determine the integrity of the data and to identify areas where additional observations were needed. Figure 11 provides an example of observations made at Level 3 of the target bay.

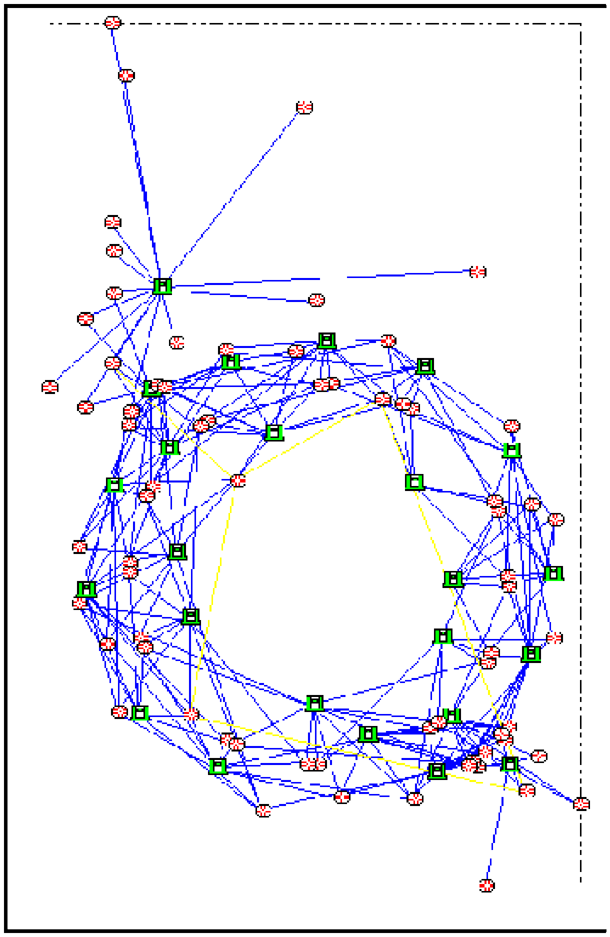

Figure 11 Observations made on Level 3 of the target bay.

After all observations were uploaded and the data reduced, a full adjustment input file was generated. The error model used for the different instruments is listed in Table 2. Note the range error for the total station was increased from 0.25 mm to 0.50 mm for distances over 50 meters. LEGO, an adjustment engine developed by SLAC, was used. The solution included earth curvature corrections from the ideal target chamber center. There is approximately a 2mm correction from target chamber center to the far end of the laser bay, 174 meters away.

The 434 instrument stations and observations (laser tracker and total station) and the measured height differences were used as input for the final adjustment. The CNM values from the Skeleton Network were used as nominal coordinates. The Skeleton Network had 133 CNMs scattered throughout the LTAB, of which twenty were in the laser bay sidewalks. The sidewalks are concrete strips surrounding the laser bay concrete slabs. The laser bay slabs did not exist when the Skeleton Network was created in June 1999. Only the sidewalk CNMs was weighted in the adjustment because of the concern with the target building displacement. Allowing the target building CNMs to float (weighted out) would prevent skewing of the coordinate system and provide relative movement in relation to the laser bays. The fit into the sidewalk Skeleton values was fairly good. Deviations of “X” and “Z” were generally less than 2 mm, even in the target bay. Deviations of “Y” were up to 4 mm due to sidewalk deformation. It appears the sidewalks displaced vertically (downward) primarily at the ends towards the target building. A couple observations were considered blunders and were weighted out.

Instrument	**Error Model**
Laser tracker range	0.050 mm
Laser tracker horizontal angle	0.1 mm / measured range
Laser tracker vertical angle	0.1 mm / measured range
Total station range (<50 meters)	0.250 mm
Total station range (<50 meters)	0.500 mm
Total station horizontal angle	0.1 mm / measured range
Total station vertical angle	0.1 mm / measured range
Digital level	0.050 mm

Table 2: Error model used in adjustment.

Figure 12 provides a plan view of the calculated error ellipses for the measured CNMs. The scale of Figure 12 does not easily show the increased magnitude of the ellipses in laser bay 2 over those in laser bay 1. In general, the CNM uncertainties in laser bay 2 are larger by about 0.06 mm (3σ). The increased magnitude of uncertainty is due to the number of observations from the laser bay to the switchyard. More observations were recorded from laser bay 1 to switchyard 1 than from laser bay 2 to switchyard 2 as illustrated in Figure 10. Construction of switchyard 2 prevented many of the same observations. Calculated uncertainties resulted in 99.2% of the CNMs at less than or equal to 0.5 mm (3σ). A few of the larger ellipses in Figure 12 are the result of single measurements or poor geometry of the observations. Figures 13 and 14 are histograms of the calculated uncertainties for the “X” and “Y” coordinates of the CNMs respectively. The histogram for the “Z” coordinates is not shown because it is similar to the “X” histogram.

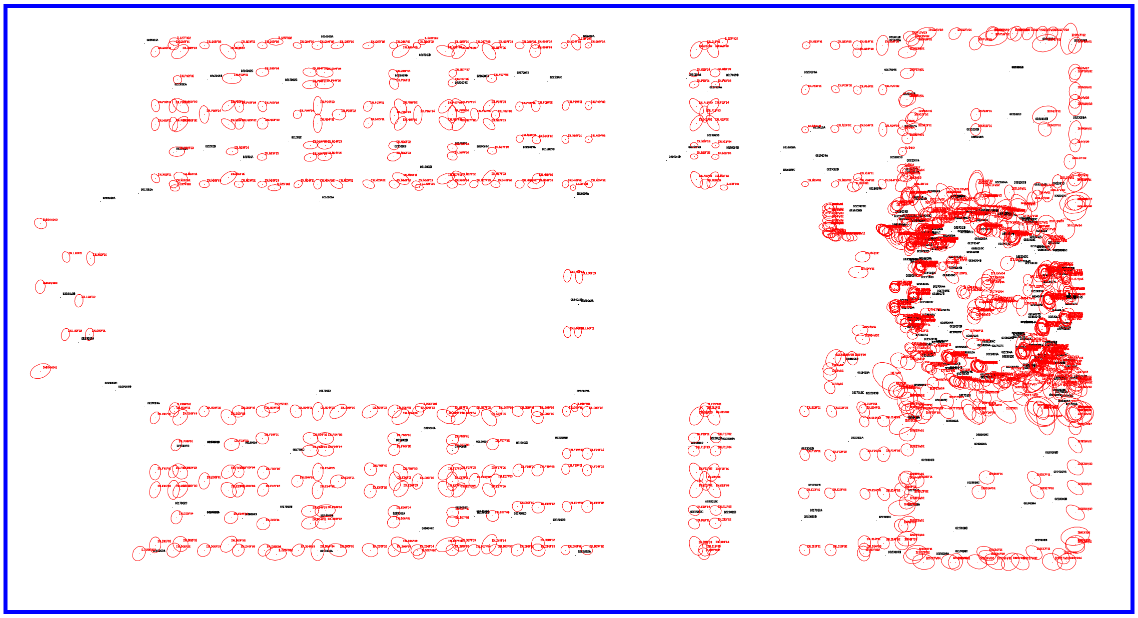

Figure 12 Plan view of the calculated error ellipses of CNMs.

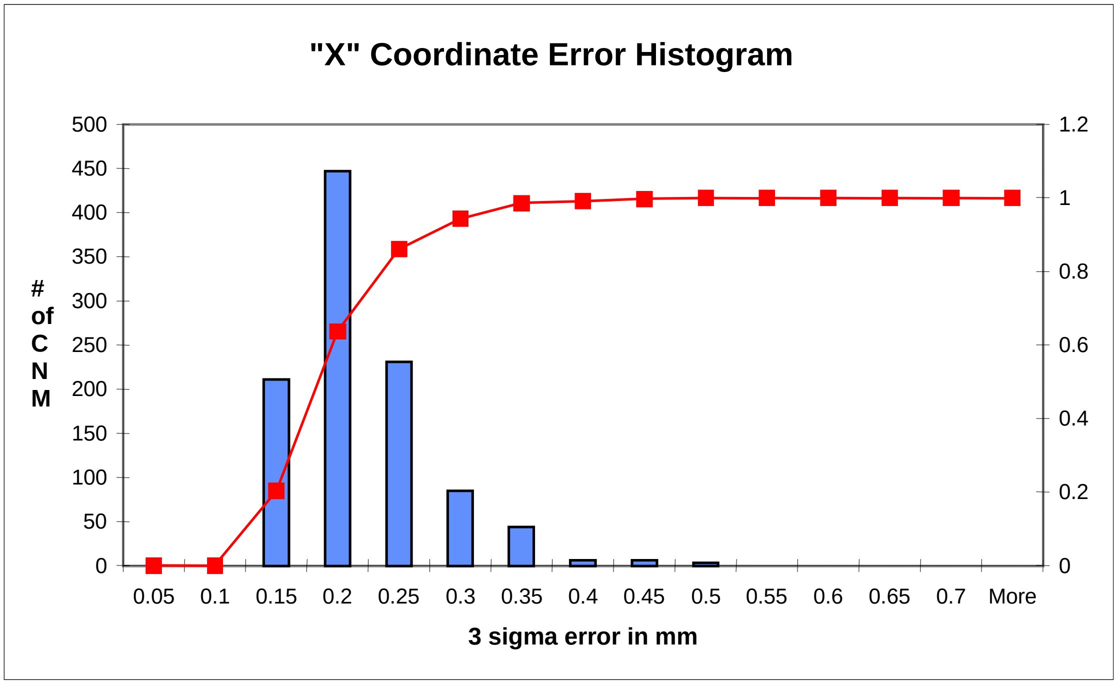

Figure 13 Histogram of "X" coordinate uncertainties in the ICN.

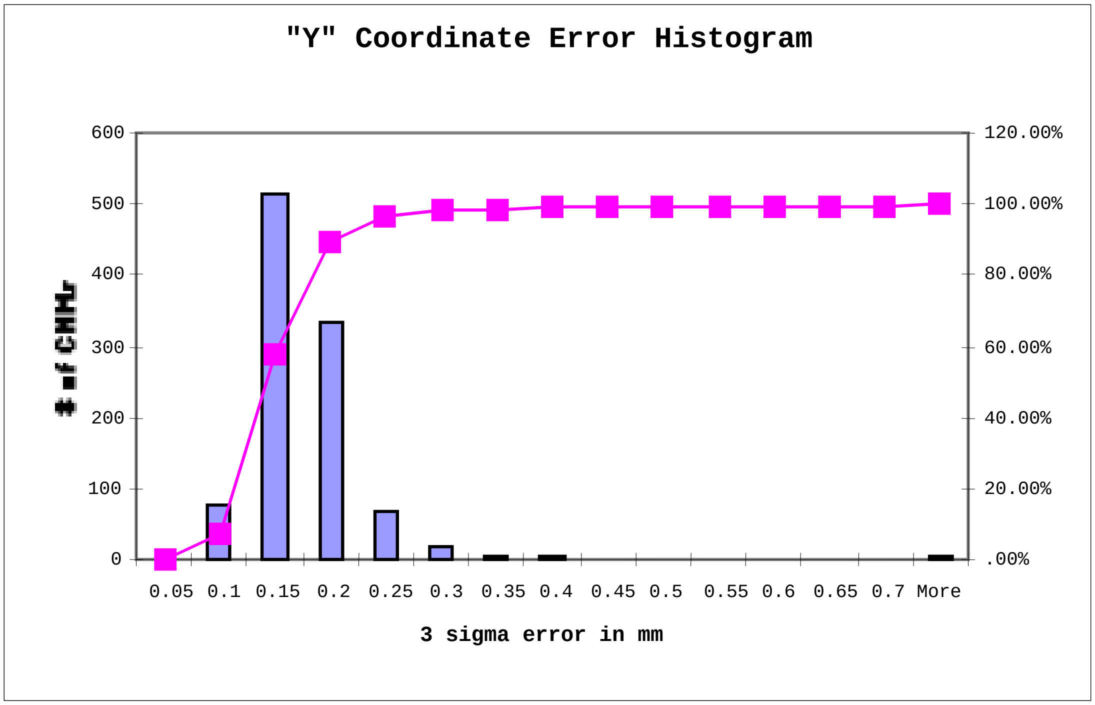

Figure 14 Histogram of “Y” coordinate uncertainties in the ICN.

In comparing the ICN CNM coordinate values to the Skeleton CNM values a fairly large downward displacement of the target building was observed relative to the laser bays. Figure 15 is a plot of displacement of three beam path locations, relative to the Skeleton Network, in the target building. The plot clearly demonstrates the differential displacement of the target building between June 1999 and March 2000 relative to the laser bays. The laser bays and the target building are built on independent concrete slabs therefore, movement is uncoupled and is primarily dependent upon the soil structure properties and loading. The observed displacement resulted in additional surveys of building construction features to determine potential interference with beam line hardware. A determination was made to lower the target chamber to minimize interference caused by building settling and out of tolerance construction.

The major contributor to the displacement is the construction of the target building itself. From October to December 1999 four of the seven levels were added to the building, the first three levels existed before October 1999. Monitoring of the building concrete slabs has continued since February of this year and results indicate continued movement. Displacement of the floors in the target building was observed after the 60 ton target bay roof was poured. Several weeks later, when the support shoring in between the floors was removed, the floor at Level 3 was observed to “spring” upward as illustrated in Figure 16. The major facility construction activities will be ending soon and the damping of deformation should occur prior to the next precision survey of the target building.

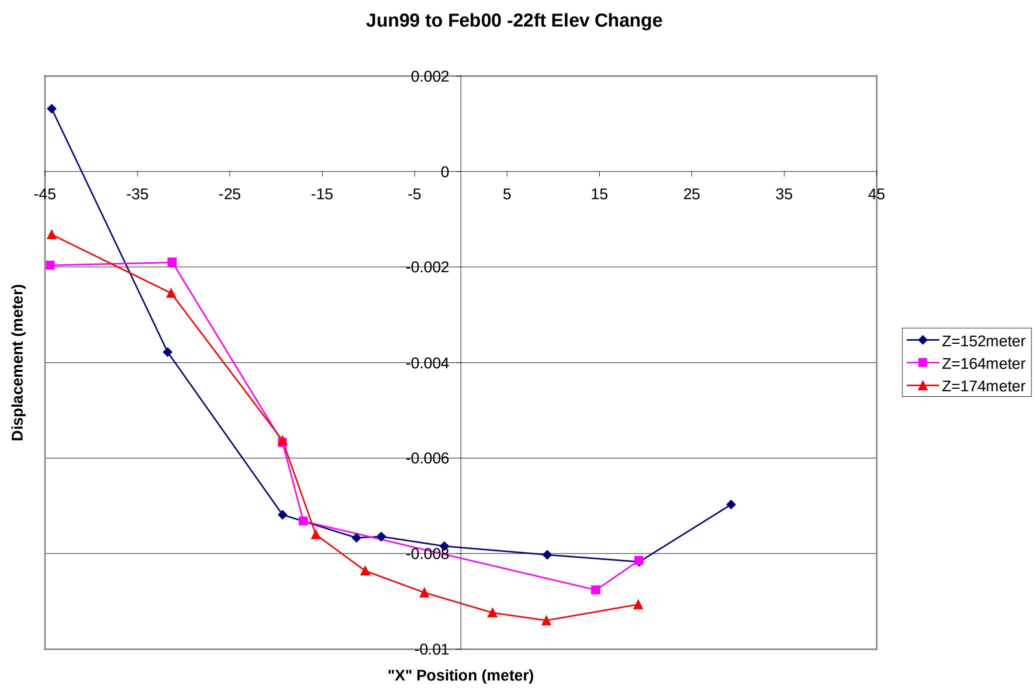

Figure 15 Differential displacement of target building relative to laser bays 1 and 2 (Jun99 to Feb00).

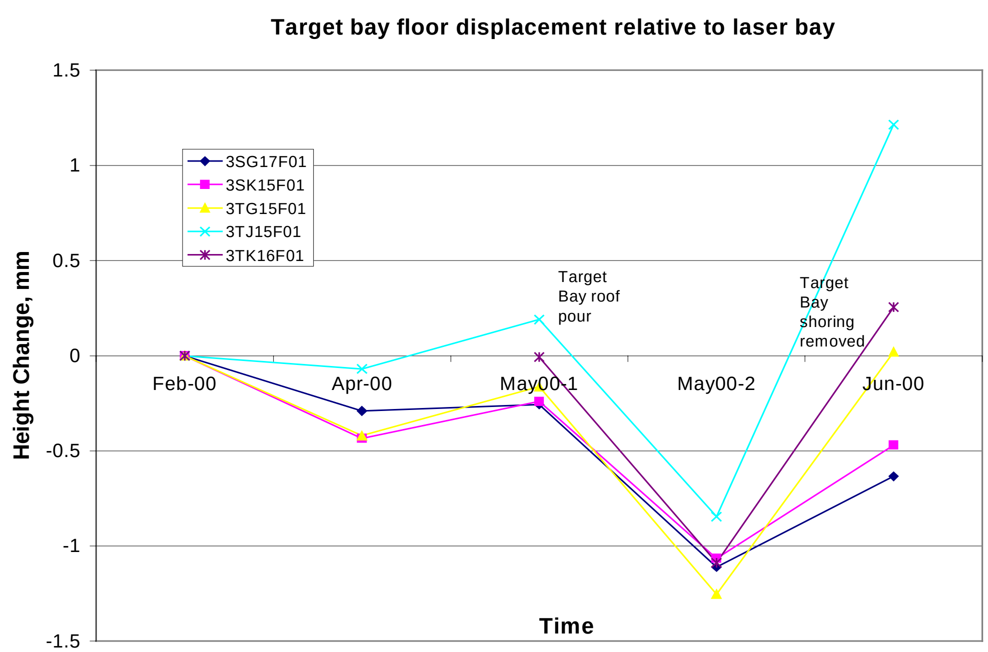

Figure 16. Time history of target bay floor (Level 3) since Feb 00 illustrating effect of roof addition and shoring removal.

Conclusions

The survey to establish the Intermediate Control Network for the NIF was a success. The requirement for $\pm$3 mm (3σ) was met with 99.2% of all CNMs known to $\pm$0.5 mm (3σ) or better. The outliers (up to 1.5mm, 3σ) resulted from limited visibility and geometrical constraints.

Performance of the Wild T2002 total stations and crews was better than expected. The standard deviation for all TC2002 distances combined was 0.117 mm; for horizontal angles was 0.94 seconds (~ 5 urad); and for vertical angles was 1.25 seconds (~ 6 urad).

The SMX 4500 laser tracker performed adequately as well considering the conditions (construction environment) and the orientation of the instrument. The standard deviation for all laser tracker distances combined was 0.039 mm; for horizontal angles was 3.6 seconds (~ 18 urad), and for vertical angles was 2.4 seconds (~ 12 urad).

The performance of the Leica NA3003 Digital Level and crew was sufficient to achieve our desired results. The standard deviation calculated for 353 heights was 0.034 mm.

Software upgrades provided by Mike Gaydosh of SLAC proved invaluable in reducing the number of field errors and the office time for finding errors during data reduction. Errors, especially typos in names, will continue to hamper the process but the software upgrades assisted in correcting many of these in the field.

Based on observations reported here, settling is not expected to threaten rough installation during CSP 13. However, settling may ultimately determine how long precision alignment can be maintained. Predictive data will be gathered by measuring building displacement once every two months. Deformation of the concrete slabs was expected, although the large and continuous movement of the target building has generated significant discussion. As a result, the target chamber center position was translated down to minimize impact with horizontal target bay penetrations. We continue to monitor floors and continue to see movements, and we have enlisted the help of geophysicists and geologists to assist in understanding the contributions of the soil properties and water table. We expect the larger displacements to decrease as major construction activities are completed.

The next challenge is to evolve the ICN to the Precision Control Network (PCN) that has a requirement of $\pm$ 0.3mm (3σ). Conditions for the survey will be better because most facility construction will be completed, the building will be temperature stable, and the laser tracker will be used more heavily in the laser bays. The planning for this survey has begun and the expectation of meeting the requirement is high based on the results of the ICN and the instrument performance.

Acknowledgements

Lawrence Livermore National Laboratory, and in particular the NIF Precision Survey Group, would like to acknowledge and thank the work and knowledge provided by members of the Stanford Linear Accelerator Center (SLAC) Metrology Department (Robert Ruland, Michael Gaydosh, and Hans Imfeld); ATT Metrology Services INC., and Johnson Controls. The combination of this knowledge base and technical competence significantly contributed to the success of this survey project.